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GROUND STRUCTURAL COUPLING TESTING AND MODEL UPDATING IN THE AEROSERVOELASTIC QUALIFICATION OF A COMBAT AIRCRAFT

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1. SUMMARY

This paper is concerned with the role played by the ground Structural Coupling Test (SCT) and the update of the aeroservoelastic model in the qualification process of a modern combat aircraft. It represents the completion of Reference 1, after several improvements introduced in the Notch Filter (NF) design procedure, numerous ground test campaigns and the confirmation of flight trials.

Most of modern combat aircraft are equipped with fly-by-wire and digital flight control systems (FCS). The problem of interaction between the dynamic response of the airframe and the FCS is usually solved through an appropriate set of notch filters, designed to attenuate the level of structure vibrations picked up by the FCS sensors. Fundamental part of the qualification of the notch filter set is the ground testing activity, generally known as ground Structural Coupling Test.

The main subjects of this paper are:

- Test Procedure
- Model update
- Describe how ground test data is used to augment model predictions in areas where the model on its own is not considered adequate for notch filter design.

2. NOTATION

ATE	Automatic Test Equipment
CG	Centre of Gravity
DOF	Degree of Freedom
FCC	Flight Control Computer
FCS	Flight Control System
FEM	Finite Element Model
FRF	Frequency Response Function
GRT	Ground Resonance Test
IMU	Inertial Measuring Unit
LMS	Loads Monitoring System
NF	Notch Filter
OLFRF	Open Loop Frequency Response Function
PC	Personal Computer
SC	Structural Coupling
SCT	Structural Coupling Test
TBD	To Be Defined
TFA	Transfer Function Analyser
U/W	Under Wing

3. INTRODUCTION

The new generation of high performance fighter aircraft relies upon digital controls, which improve their handling and manoeuvre capabilities, and allow unstable aeroplanes to fly. To achieve these functions the aircraft FCS is designed to generate a feedback based on the analysis of signals coming from IMU sensors. Since the IMU is fitted to the elastic airframe, its sensors, besides the aircraft rigid body motion parameters, pick up also the structure vibrations. The concept of system stability must be therefore extended to the full system, including the aerodynamic and mass characteristics of the aircraft, the FCS and the structural dynamics of the airframe.

Among the forces that cause the airframe dynamic response, the aerodynamic and inertial forces induced by oscillating control surfaces play a fundamental role. They in fact give rise to a very dangerous loop when exciting the structure near a resonance. This can occur when signals from IMU are not appropriately filtered to remove structure vibration contents,

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inducing, through the feedback to control surface actuators, those oscillations that must be avoided.

SC is the discipline developed to study the coupling between the dynamic response of the airframe and the FCS, and plays a very important role in the qualification of aircraft with digital controls. The usual solution to SC problems is to implement a set of NF in the FCC and IMU control laws, in order to attenuate to a safe level the airframe vibration contents in the signals running in the FCS. Reference 2 illustrates the procedure developed and applied for the design and qualification of NF. A fundamental step of this procedure is the ground SCT stage, the aim of which is to identify the SC characteristics of the aircraft. Data from SCT are required for the updating of the aeroservoelastic model to be used for the NF upgrade. Ground test data are also essential to improve the design in the high frequency range, where the model predictions are not considered adequate.

4. GROUND STRUCTURAL COUPLING TEST

The main objectives of the ground SCT are to provide data for:

- Model validation
- Investigation of unmodelled aspects
- Coverage of the frequency range where the model alone is not considered to be an adequate basis for production of filter design information.

The amount of analysis to be carried out using the aeroservoelastic model is really huge. Calculations are in fact required for NF design and optimisation, and subsequently for flight clearance and qualification purposes. Considering the wide possibility of combinations of external stores for a military multirole aircraft, which strongly influence the dynamic response characteristics of the airframe, it is evident that only a limited set of external store configurations can be tested on ground, the rest being studied only through calculations. The consequence is the need of an adequate mathematical model for SC analysis and methods to augment the model predictions using a limited set of test data.

The main objective of the ground SCT is therefore to get all information needed to evaluate how the model simulates the SC characteristics of the aircraft in absence of aerodynamics, and then to update the model and the preliminary NF, if necessary. The other important objective is to collect enough experimental data in the high frequency range. It is well-known, in fact, that the quality of the model predictions above a certain frequency is rather poor. Since the NF are to be implemented in a digital system the frequency range that must be covered in their design depends on the sampling rate of the FCS and, as a consequence, the analysis is to be extended usually beyond the model capabilities. During the Identification Test the measurement of transfer functions is performed also covering the frequency range where the model is not satisfactory. The relevant experimental data will feed a procedure developed to augment model predictions, based on the direct usage of experimental data combined with model predictions, as more fully described in section 6.

Additionally, the test is very important to assess the influence on the aircraft response of structure non-linearity, hydraulic failures, control surface trim position, actuator hinge backlash, undercarriage support, etc., not implemented in the linear model.

Essentially the test consists in measuring the IMU signals in response to the excitation of the aircraft, obtained by means of sinusoidal rotation of control surfaces about their hinge axes. This gives rise to inertial forces due to the surface CG offset with respect to the hinge axis, and makes the structure respond at the same frequency of the surface oscillation. The relevant vibration levels are picked up by the IMU sensors, measured and then used to calculate the transfer functions corresponding to those employed for the preliminary NF design. The test is carried out in open loop, to avoid IMU signals being sent to the FCC and therefore to the control surface actuators. This stage of testing is referred as the *Identification Test*, because it serves to identify the SC aircraft characteristics and it must be performed quite early with respect to the flight date, depending on the time required for the updating of notch filters.

A further SCT stage is usually foreseen in the route to clearance just before the first flight, called *confirmatory test*, the aim of which is to verify that the updated NF satisfy the requirement for the aircraft in the pre-flight standard. This test is necessary when significant structural changes are introduced, above all in the mass distribution, between pre-flight and identification test aircraft standard.

The following paragraphs will be devoted to describe more in detail all the aspects which are typical of ground SCT.

4.1 Aircraft Build Standard

The aircraft to be tested must be representative of the flight standard with regard to the mass distribution and the airframe stiffness. Since the identification test is usually carried out several months prior to the first flight, it might be that some equipment are missing or not available at that time. Appropriate ballast should be fitted to substitute the missing items, which with their weight can influence the aircraft response. One of this is, for instance, the pilot with his flight equipment. It is particularly important that mass of equipment located at the extremities of flying surfaces - for example the wing tip pods on Eurofighter – is correctly represented since these have a significant effect on the aircraft flexible mode frequencies and structural coupling characteristics.

Concerning with the stiffness, it is essential that all panels and doors carrying loads must be closed and fixed. Since during the test it is required the access to some equipment for cable connection (FCC, IMU), power supply and inspection, it might be necessary to build spare structural panels with stiffened holes, in order to maintain the stiffness characteristics and fulfil the access requirements.

The peculiarity of the SCT is the excitation, that is obtained by means of the oscillation of the control surfaces. For this reason it is necessary to have the hydraulic and electrical plant perfectly functioning and the flight actuators installed. The power supply to these systems is obtained by means of external devices that will be connected to the aircraft.

Other essential components needed for the test are the FCC and the IMU, each one with the appropriate hardware and software standard. The FCC at this stage is only needed to manage the excitation signal generated from the test equipment, driving it to the actuators. Since the control laws are not involved in the test procedure a preliminary FCC software version can be accepted.

4.2 Aircraft Suspension

The aircraft must be tested in free-free condition, and this can be accomplished using an elastic suspension or pneumatic supports. The suspension must be designed with a response frequency quite below the lowest modal frequency of the aircraft, in order to avoid any interference with the airframe response.

Some test runs might also be repeated on undercarriage, to evaluate the influence of this system on the aircraft response. This approach can result to be very helpful for the confirmatory test phase, when very few runs are required and therefore the test could be carried out, in order to save time, using the undercarriage support. The aircraft response in free-free condition can then be derived from the differences between free-free and on-undercarriage responses measured during the identification test.

4.3 Special Requirements

During the SCT some parameters must be kept under control, in order to avoid damage to the aircraft. For instance, control surface actuators are driven in a manner which is quite different compared with normal operation during the flight for the aircraft control, and some actions are to be undertaken to avoid an excessive drying of actuator ram seals. The risk is in fact that these parts are not lubricated as required, because of the small amplitude of motion of the ram at high frequency. The solution to the problem is to interrupt the test after that the actuator rams have performed a certain number of cycles, fixed by the relevant specification, and lubricate the sealing carrying out a run characterised by few cycles at wide amplitude and very low frequency. Considering that the number of cycles allowed between two lubricating cycles is reached quite rapidly, above all at high frequency, the lubricating cycles are carried out rather frequently during the SCT. This of course slows down the test and compels to split it into several runs.

Engines are other items that need attention during the test, in order to distribute effects of vibration wear on bearings and rotating parts, that during the test are obviously at rest. This is usually accomplished by rotating periodically the shafts of the engine during the test, using crank systems or any other device that allows the rotation of the engine shafts.

During the SCT high vibration levels might be reached in some parts of the airframe and maintained for several cycles. For this reason it is necessary to monitor these levels by means of a set of accelerometers and strain gauges, located at aircraft structure critical points. These sensors send the signals to a device, which automatically cuts out the excitation when it realises a dangerous situation for the aircraft. In particular, each channel is set to the level of acceleration or stress, that must not be exceeded at the relevant airframe point and a continuos comparison is performed between these thresholds and the signals coming from the sensors. Whenever a threshold is exceeded, the device generates a signal which causes the cut-out of the excitation. Usually the thresholds correspond to the *fatigue negligible limits* of the elements of the structural component: if they are not exceeded during the test no fatigue damage is caused to the structure. If the excitation is not high enough to obtain an adequate response of the structure it is necessary to increase the excitation level beyond these limits: in this case the signals coming from the sensors must be recorded for subsequent evaluations on the fatigue damage caused to the structure. The thresholds in this case are increased up to a certain percentage of the negligible limits, never exceeding the *maximum limits*, provided together with the negligible limits.

4.4 Excitation Procedures

SCT is unusual in the manner in which the dynamic response is excited. The inertial forces which excite the aircraft are generated making the control surfaces oscillate about their hinge axis. To do this a sinusoidal signal is generated by the test equipment and then sent to the control surface actuators through an appropriate setting of FCC. The control surfaces are not moved all at the same time, but they operate in couple or single, depending whether they are symmetrically located on both sides of the aeroplane or not (rudder). Two different types of excitation can be considered: symmetric, sending the same signal to the two surfaces of the couple; anti-symmetric, sending signals with same amplitude but shifted in phase of 180 degree. With this approach it is possible to excite separately the symmetric and anti-symmetric modes of the airframe. Figure 1 shows the different combinations of control surfaces and the relevant IMU signals measured to calculate the OLFRFs.

The aim of the test is to identify how the principal modes of the aircraft respond to this kind of excitation To fulfil this task a sine step sweep procedure has been adopted, changing the frequency of the signal with discrete steps and maintaining the same signal for a certain number of cycles, during which signals from IMU are measured. The Sine Step method has shown to be more appropriate than a sine continuous sweep with logarithmic frequency variation, because it allows to gather data for more cycles at each frequency and consequently a better average of the aircraft response.

The amplitude of the oscillation must be set sufficiently high to obtain the level of forces needed for a proper response of the aircraft, while avoiding actuator non-linear effects. In general, excitation amplitude is high at low frequency, and diminishes as frequency increases, in order to respect the LMS constraints. The approach normally followed to obtain the best response of the structure is to maintain the level of the excitation amplitude as high as allowed by the LMS constraints. Some preliminary runs are dedicated to optimise the amplitude of the sine sweep: starting from a TBD value at low frequency, the run is repeated increasing every time the level of amplitude, until the LMS cuts off the input signal. On the basis of this level an appropriate amplitude profile versus frequency can be defined, following two opposite necessities: to keep the amplitude as high as possible and to avoid a continuos interruption of the test by the LMS

4.5 Preliminary Checks

Many checks must be carried out prior to start with the SCT, in order to verify that all test equipment and instrumentation items are working in accordance to the SCT specifications.

An assessment of the mass characteristics of the aircraft is required in order to update the representation of mass in the mathematical model. This will require a measurement of the total weight and cg position of the aircraft. A check is necessary to ensure that the mass of equipment located at the extremities of flying surfaces - for example the wing tip pods on Eurofighter –is correctly represented since these have a significant effect on the aircraft flexible mode frequencies and structural coupling characteristics. A detailed monitoring of the aircraft build standard up to the time of the tests is therefore needed.

Control surface actuator hinge backlash tests are required prior and after the test, to verify that the surface oscillations have not caused any damage to the hinges.

It must be verified that the FCC feedback loops are opened, and this can be done by simply *hand rocking* the aircraft in pitch, yaw and roll. From the analysis of FCC signals that indicate the position of control surfaces it can be deduced whether they are moving or not: of course, since no external signal is sent to the actuators, a movement of the surfaces would mean that a feedback signal is sent by the FCC to them, and that therefore the loop is closed. Since the test must be carried out in open loop, the FCC setting has to be reviewed and the check repeated if the open loop condition is not verified.

Another important check regards the by-pass of the IMU NFs. Preliminary NFs are in fact implemented in the FCC and IMU control laws and all facilities provided for their by-pass must be activated. To verify the effectiveness of the by-pass procedure, some runs must be repeated in the frequency range where IMU NFs are active, with the by-pass on/off: if the NFs are correctly by-passed the appropriate attenuation has to be found when comparing the OLFRF measured with the by-pass active with respect to the one without by-pass.

The last stage before starting the SCT consists in measuring the transfer function of each actuator, to verify that the relevant performances are in accordance with previous rig tests.

4.6 Aircraft Identification Test

The OLFRFs to be measured are defined by the procedure for the NF design , and can be deduced from the sketches reported in Figure 1. They must be measured in a frequency range extended up to the sampling rate which characterises FCC digital signals. This is necessary to take into account the folding-back effect of the high frequency range due to digitalisation.

To carry out the SCT it is necessary to exchange data with the FCC and this function is performed by the ATE, a device designed for pre-flight FCC checks and able to perform the following operations during SCT:

– set up and read/write FCC parameters
– injection of the excitation signal into the FCC
– reading of IMU sensor signals from FCC facilities
– real time presentation of FCC signals.

The excitation signal is generated by a TFA, incorporated in the ATE and interfaced with an external PC. The same TFA performs the calculation of the OLFRFs and sends the relevant data to the PC for storing and subsequent analysis. Figure 2 illustrates the layout of the test, showing the links among the test items and the exchanged data. During the test measured OLFRFs are compared with theoretical predictions, in order to check whether unexpected or unwanted effects are influencing the test.

It is very important to verify the degree of non linearity of the aircraft response during the test, looking at the shape of IMU and LMS sensor time histories traced in real time by a brush recorder. More detailed information are obtained repeating some runs, usually for the most important normal modes, at different amplitude levels. The lesson learnt from the SCT is that the highest amplitude levels compatible with LMS constraints should be used, to keep non linearity effects to a minimum level. Figure 3 shows the same OLFRF measured at different amplitude levels in the first wing bending frequency range, highlighting that the main effect of non linearity is on the amplitude of the peak, with small influence on the frequency.

Besides the influence of amplitude other test runs are to be carried out, in order to investigate the influence of failures of one or two of the four redundant hydraulic systems and FCCs. These checks are needed since in this case the actuator performances can present significant changes, influencing the OLFRFs and thus the NF design.

4.7 Confirmatory Test

The *identification test* covers all the aspects necessary to identify the SC characteristics of the aircraft required for the NF design. It is very detailed and carried out for different aircraft configurations, regarding both external stores and internal fuel. This is done to verify the theoretical predictions relevant to the influence of mass characteristics on the aircraft response.

On the contrary, the *confirmatory test* is intended to be a very short test, with the aim of verifying that the aircraft in the ready-to-fly standard does not present significant changes in the response with respect to the *identification test*. The test is therefore to be carried out when the aircraft is in the flight configuration. The verification test is normally limited to modes that are very sensitive to mass distribution changes and that play a leading role in the NF design. It consists in a short *identification test,* limited to few modes, selected as most critical from the NF design point of view.

The confirmatory test is the last step in the NF qualification route before flying the configuration investigated. It is needed to issue the SC flight clearance: from the analysis of the test results it will come out whether the NFs, based on data from the *identification test,* can be confirmed for flight or not, and a reassessment for worst flight conditions can be necessary. In the worst case flight limitations might result for some regions of the flight envelope.

5. UPDATING OF THE AEROSERVOELASTIC MODEL

To accomplish the NF design procedure the OLFRFs relevant to external store configurations are required. Considering the number of configurations and the possible sub-configurations deriving from store release, it is essential the development of a reliable aeroservoelastic model to perform the amount of calculations required for the NF design.

Among the components of the aeroservoelastic model there is the aircraft structural dynamic model, the updating of which is discussed in this paper. The basis of this model is the Nastran Superelement Technique, which allows to design simpler models and then to assemble the final model with a linking procedure. In the case of the Eurofighter the airframe has been divided in the following superelements:

- wing, including flaperons and slats
- fuselage
- foreplane
- fin and rudder
- U/W pylons

Each superelement consists in a mass and stiffness matrix, calculated using the relevant FEM and applying a reduction to a set of DOFs. The dynamic reduction of the model is a very important stage, since it allows a drastic reduction in the number of DOFs, leading to a simplified model. The DOFs selection must be performed following the guideline that the reduced model has to simulate adequately the structural dynamic characteristics of the component in a certain frequency range. Some trials might be required before a satisfactory result can be achieved.

5.1 Model Updating on the Basis of GRT Results

The GRT results represent the basis for the updating of the dynamic model. All the remarks that follow about the model updating, are based on the activity performed after the GRT and SCT campaigns carried out on the first U/W stores configurations to be cleared.

Considering that component GRT for wing, fin, foreplane and pylons, had already been carried out and the relevant superelements updated, the GRT on the assembled aircraft was required to gather data for the updating mainly of the fuselage superelement and of all the elastic elements used to simulate, in the assembled model, the links among the superelements. Figure 4 is a sketch of the superelement model updating activity performed before the GRT on the aircraft. At this stage a preliminary updated model was available and it was used to predict the response of the aircraft during GRT and SCT. It was also employed to carry out all calculations required for the preliminary NF design. Figure 5 illustrates the next step, carried out after the GRT and concerning with the delivery of the final updated model, including all the effects not covered during previous superelement GRTs.

From a first rough look at the aircraft GRT results it came out that the model had the general trend to predict lower modal frequencies. The differences between test results and predictions indicated that a model adjustment was necessary. The correction was obtained applying factors to the superelement stiffness matrices and updating the mass distribution of the model, the latter based on the assessment of the aircraft mass distribution carried out before starting the test. Several trials were needed to find a set of factors for the superelement stiffness matrices, but eventually this approach demonstrated to be adequate to obtain satisfactory results. The factors were all greater than one, the greatest being applied to the fuselage, and the updated stiffness matrices were obtained multiplying all their elements for the relevant factor.

Before starting with the updating procedure it was necessary to manipulate the experimental data, transforming the GRT modal shapes in perfectly symmetric and anti-symmetric modes. This step was needed since the aircraft model is a representation of half aircraft. The main problems with asymmetry in modal shapes came from modes characterised by external stores and control surfaces wide motion. For these cases the approach was to consider data coming only from the accelerometers located on the side of the aircraft which showed a better *phase index*.

The correction procedure was iterative, starting with an initial set of factors. The new model was assembled using the factored superelement matrices and modal characteristics compared with those ones measured during the GRT. From this comparison a new set of factors would be defined and the process repeated until a satisfactory comparison could be found. The modal characteristics monitored during the iterative procedure to establish when the process could be stopped were the modal frequencies, the generalised masses and the modal shapes.

Regarding the frequency, the comparison was based on the percentage difference between test and model data. Figure 6 shows the situation for some modes at the end of the procedure, pointing out to the improvement obtained for this parameter with respect to the GRT predictions.

For the comparison of the generalised masses and the modal shapes it was necessary to renormalize the theoretical modes, in order to make them homogeneous with the measured ones. In general the location of the accelerometer with the highest response level was chosen as reference point. This step was repeated for different points, depending on the modal shape and the accelerometer phase index measured during the acquisition of the mode. The aim of this repetition was to understand how the selection of the reference point could influence the calculated generalised mass. To perform these checks without problems the GRT accelerometer map was designed making the accelerometer locations coincide with model grids whenever it was possible. This approach could be easily followed for components like wings, foreplane and fin, but for the fuselage an interpolation of sensor data was necessary. For the comparison of modal shapes the following index was calculated:

$$\frac{\left(\Phi_{theory} \bullet \Phi_{GRT}\right)^2}{\left|\Phi_{theory}\right|^2 \times \left|\Phi_{GRT}\right|^2}$$

where Φ_{theory} and Φ_{GRT} are the two eigenvectors to be compared.

In the updating procedure a special attention was dedicated to the most significant modes, namely those ones that in the previous analyses had shown to have a considerable influence on flutter, SC and dynamic loads. This approach allowed to obtain a model that can be considered adequate for general dynamic analyses, the modes represented by the model with less precision being not essential for the study of aeroservoelastic criticality.

Since the issue of Reference 1 several GRT and SCT campaigns have been performed, each one devoted to investigate a set of critical store configurations, followed by further updates. As expected, the corrections were necessary only to those items, like pylons and launchers, not tested before and there was no need to touch the baseline aircraft model updated after the first GRT campaign.

5.2 Model Updating on the Basis of SCT Results

Progressing with the development of the aircraft the necessity to cover more stores configurations with the same set of filters became the most challenging problem to solve. This is also the final target: a unique set of NF able to guarantee the required gain and phase margins for all configurations. It was immediately evident that this was a difficult task, and a less conservative approach was necessary, starting from a better correlation of the Structural Coupling model with SCT results. Moreover, the introduction in the design procedure of the Phase Stabilisation concept (Reference 2) required also to validate the phase predicted by the model for the low frequency modes, extending the comparison also to the phase of the OLFRFs.

The SCT is in general performed in parallel to the GRT, but not necessarily on the same configurations. The aim of the GRT is in fact to collect enough data for the modal identification of the aircraft, and in particular for specific items like pylons and launchers. In this case single store configurations are acceptable. For the SCT, since the high frequency measurements are used directly in the notch filter design, the configurations must be representative of the most critical ones, previously identified by the model.

Immediately after the release of the model updated on the basis of GRT, the next step is the simulation of the SCT runs carried out on ground, using initially the modal damping values measured during the GRT. At this stage a further improvement is introduced in the aeroservoelastic model, replacing the actuator transfer functions with the frequency functions measured during the preliminary phase of the SCT. These frequency functions are thus compared with the test data.

In general the correction is needed only to match the amplitude of the main modes responses, the frequency being already corrected during the GRT updating. No attempt is made to correct the phase, but simply a monitoring of main modes to confirm the applicability of the Phase Stabilisation concept.

The first step in the correction of the SC model is to identify the possible source of errors in the model and next to find a procedure simple enough to obtain a satisfactory result across all of the several configurations to be covered. The source of errors considered for the model correction are the following:

- Fuselage model and IMU location.
- Modal shapes.
- Non linearity effects.

The first point is very important, but difficult to address. The superelement representing the fuselage is in fact reduced to a limited number of grid points along the longitudinal axis representing the main structural stations, and other grid points located at the position of main equipment items to simulate their mass and inertia characteristics. Among the latter there is the IMU grid point, but trying to match the SCT results changing the elements of the stiffness and mass matrices was not considered practical. Another approach was tried, applying appropriate factors to the modal deformations of the IMU grid point, but a satisfactory solution was not found, principally because the factor affected all OLFRFs whereas the error in each mode is different for each control surface / sensor combination. This result confirms that the correction of only the fuselage modal shape is not enough and, since the inertial excitation induced by the oscillating surface depends on the modal response of the aircraft, a more general correction is needed. However, in order to generate a reliable model, the location of sensors and the fuselage model must be considered with great care. Concerning with the modal shapes, the matching of the main modal frequencies was considered a success, since the optimisation of the model with the modes as constraints at the current state of the art is feasible only using very simple dynamic models.

Another aspect to be considered in the model updating is the effect of non linearity on the test results. As explained in the description of the SCT procedure, excitation amplitude varies with frequency. This means that, if the effect of the non linearity of the system is significant, the comparison with the model is affected by an error distribution that depends on the frequency. For the most important modes this effect is assessed repeating the surface excitation at different input levels. In general the effect on the frequency of the mode is small, but on the amplitude of the response is significant, and should be taken into account. The general approach is to consider the amplitude associated to the highest level of excitation and to change the original GRT modal damping values according to SCT data.

On the basis of the above discussion it has been decided to adopt a data base of frequency dependent response-amplitude correction functions, to be applied to the OLFRFs calculated by the model. The data base is generated according to the following procedure:

- The data base contains several sets of correction functions, one set for each store configuration tested on ground during the SCT.
- Each set contains one correction function for each OLFRFs, calculated comparing the measured and the related analytical OLFRFs.
- The data base contains also a set where each correction function is the envelope of the corresponding functions calculated for the tested configurations. This set will be used for configurations not tested during the SCT.

The OLFRF correction process consists in performing the product of each OLFRF for the associated correction function before the filter optimisation phase. This approach allows the correction of the structural uncertainties of the model. Figure 7 is an example of how this method is applied. The picture shows the typical situation encountered during the correction procedure: a very good matching of the model for the first modes and the necessity to introduce a correction for the modes close to the frequency limits of application of the model.

A further correction can be implemented after the structural coupling flight trials have been completed. This correction is much simpler, being associated to the efficiency of control surfaces, generally overestimated by the model. A factor can be identified for each significant mode and applied for all configurations, since the effect of stores on these factors can be accepted as negligible. The main difference between the structural and the aerodynamic correction is that the first is represented, generally speaking, by an amplification factor, the second by an alleviation factor. Figure 8 illustrates this characteristic from the comparison of model predictions with flight test data. It gives an idea of the degree of conservatism of the model, from which the aerodynamic alleviation factors can be derived.

The procedure described, even though complex, is very practical and easy to be implemented in a global automatic procedure for the generation of the OLFRFs needed for the NF design. Its weak side is represented by the management of a data base with data associated to several stores configurations and the necessity to identify the most critical configurations to be tested on ground. The number of critical configurations can be significant and the dependency on ground testing is a heavy burden in the qualification of a multirole aircraft. For future aircraft an improvement in the structural and aerodynamic modelling techniques is necessary, in order to reduce the cost and the risks inherent in the design and qualification of notch filters.

6. REPRESENTATION OF HIGHER FREQUENCY RANGE

Under the current Eurofighter notch filter design philosophy and procedure (Reference 2), the OLFRFs derived as described in Section 5, i.e. wholly from the flexible aircraft model, are used only for representation of the lower frequency modes, which are critical for notch filter design and which have the most significant impact on the notch filter phase lag.

For higher frequency modes the model is not considered reliable enough for use in a 'stand alone' manner, and an alternative approach is taken which combines ground test-measured frequency response functions with model-predicted aerodynamic effects and calculated FCS control law gains to form a conservative representation of the overall system.

This approach avoids the difficulties associated with a model update that aims to;

- be rational and physically meaningful, and
- lead to a single model able to reproduce measured responses in several different sensor / excitation combinations.

In the applying the method, it is assumed that the predicted aerodynamic effects, in terms of gain change as a function of airspeed, are correctly predicted by the model, and that it is fundamentally the zero-speed characteristics which are in error when compared with ground test results. Thus the method effectively substitutes the measured zero speed characteristics for the predicted, producing a composite FRF which, when the FCS gain is included, can be used for Notch Filter design.

6.1 Aerodynamic Effects

Flexible aircraft response to control surface excitation is calculated across a range of flight conditions, covering the desired flight envelope (extended to encompass Mach and height overshoots). The combinations of sensor output and control surface input required are determined by the control law configuration. These combinations are identical to those defined for ground SCT, Figure 1.

Aerodynamic effects are derived from the FRFs in the form of increments in predicted response-peak gain and frequency, relative to the corresponding zero-speed characteristics. This results in a presentation of response gain and frequency trends for each mode and sensor / control surface combination, which, when combined with the corresponding FCS gain schedules, gives a clear and concise view of the variation of overall response, and by implication gain margin, with speed.

The calculation can be made with a preliminary, pre-SCT, model standard, facilitating early progress with notch filter design, but careful checks must be made where the actual (SCT measured) modal frequency separation is found to vary significantly from prediction, implying differences in mode shape and hence in the unsteady aerodynamics.

6.2 Zero Speed Characteristics

Clearly, successful application of the method will depend on both the quality of the ground structural coupling test data and the correct identification of the correspondence between modes excited in the ground test with those predicted by the model. Particular attention must be paid to both of these aspects in the conduct of the ground test, implying close involvement of structural coupling specialists in the tests.

7. CONCLUSIONS

The test procedure followed for the SC identification test of a delta-canard aircraft has been described. The need for an accurate aeroservoelastic model, in order to limit the testing activity to a reduced number of external store configurations, selected on the basis of SC criticality, has been pointed out. The way followed to update the theoretical model using Ground Resonance and SC Test results has been presented. The aeroservoelastic model, updated with test data, can be considered a reliable tool for the FCS NF design in the low frequency range, where the most critical modes can be found. For the high frequency range a method, based on a combination of test and model data, has been described. Its application allows to contain the model deficiency in this frequency range.

The updating procedure described in this paper is based on two steps: the first mainly on the correction of the stiffness characteristics of the model, using data gathered during GRTs carried out on a limited number of external store configurations. This set of configurations of course must be selected so to cover the stiffness characteristics of all pylons and launchers which can significantly influence the airframe dynamic response. The second step refers to the generation of a data base of correction FRFs derived from the comparison of model predictions with SCT data.

Following this approach all not tested combinations of stores can be studied using the mathematical model, by the simulation of the appropriate mass distribution, and thus limiting to a limited number of critical configurations the very expensive test activities. For the high frequency range it is essential that the configurations tested on ground are the most critical for SC aspects, and therefore the measured data can be used also for the remaining configurations.

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9. B.D.Caldwell, R.Felton, “Validation of FCS Structural Coupling Stability Characteristics Through in-Flight Excitation”, CEAS International Forum on Aeroelasticity and Structural Dynamics, Rome, 17-20 June 1997

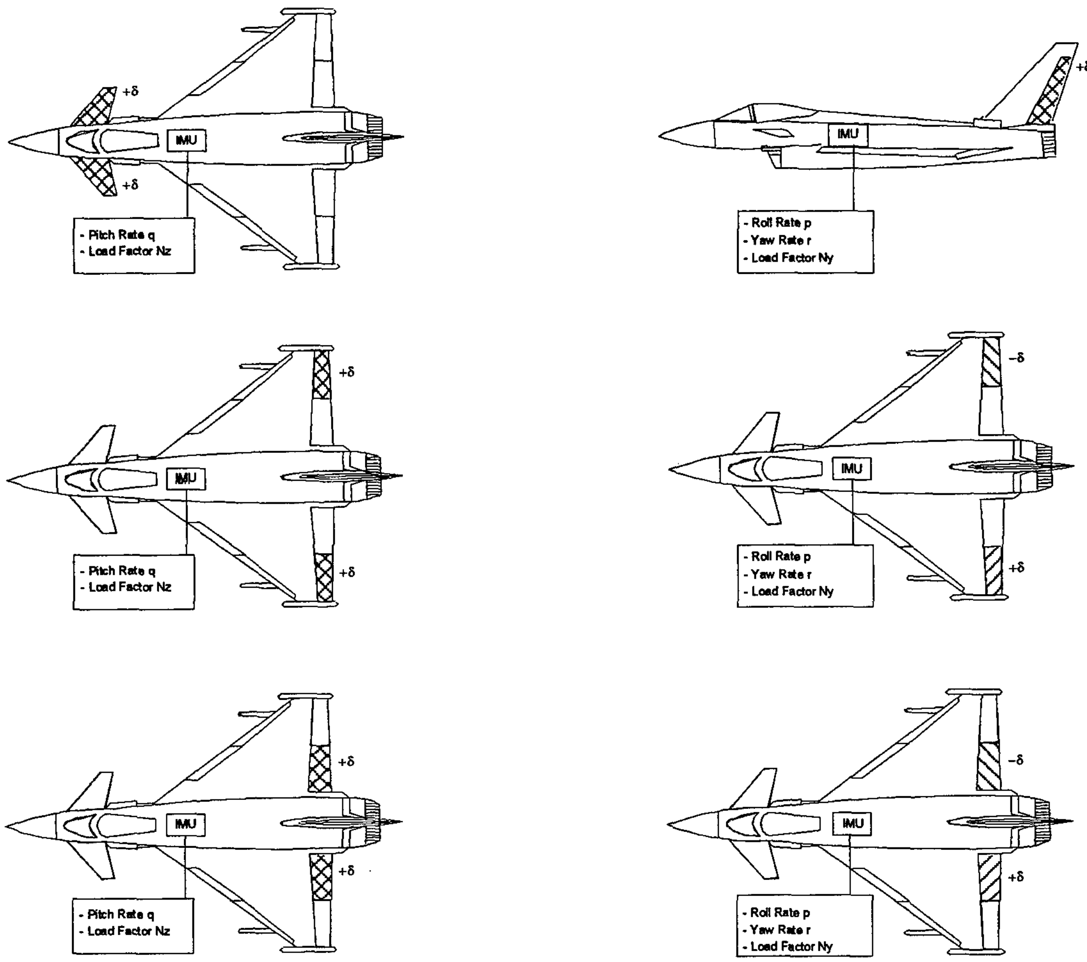

Figure 1: SCT and Antisymmetric Symmetric Excitations and Measurements

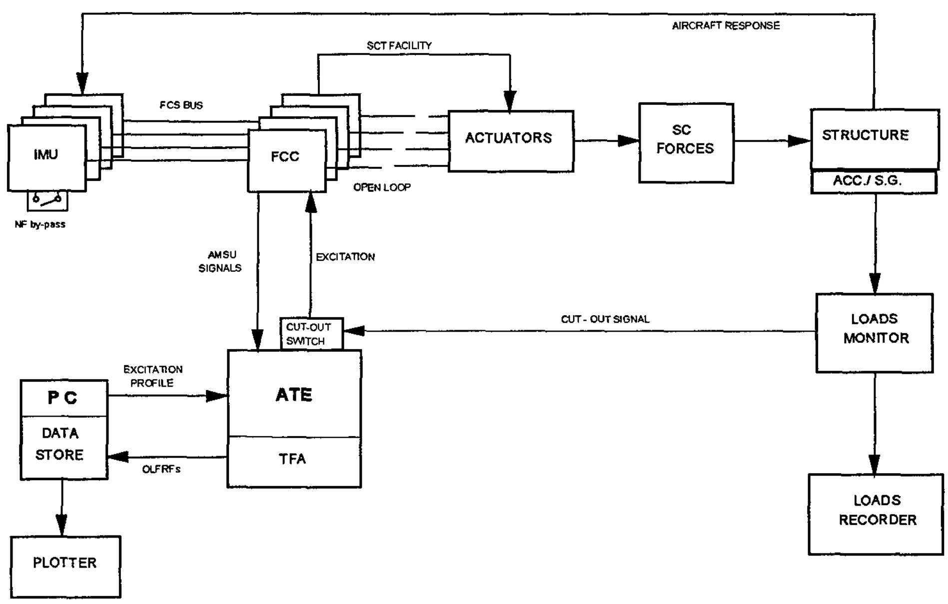

Figure 2: SCT Layout

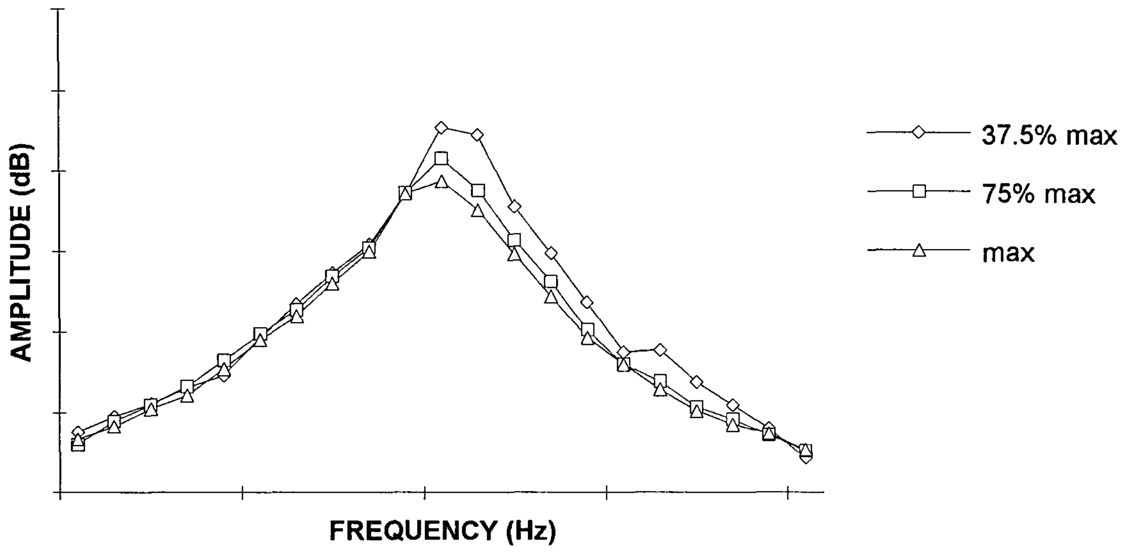

Figure 3: Influence of Excitation Amplitude on OLFRF

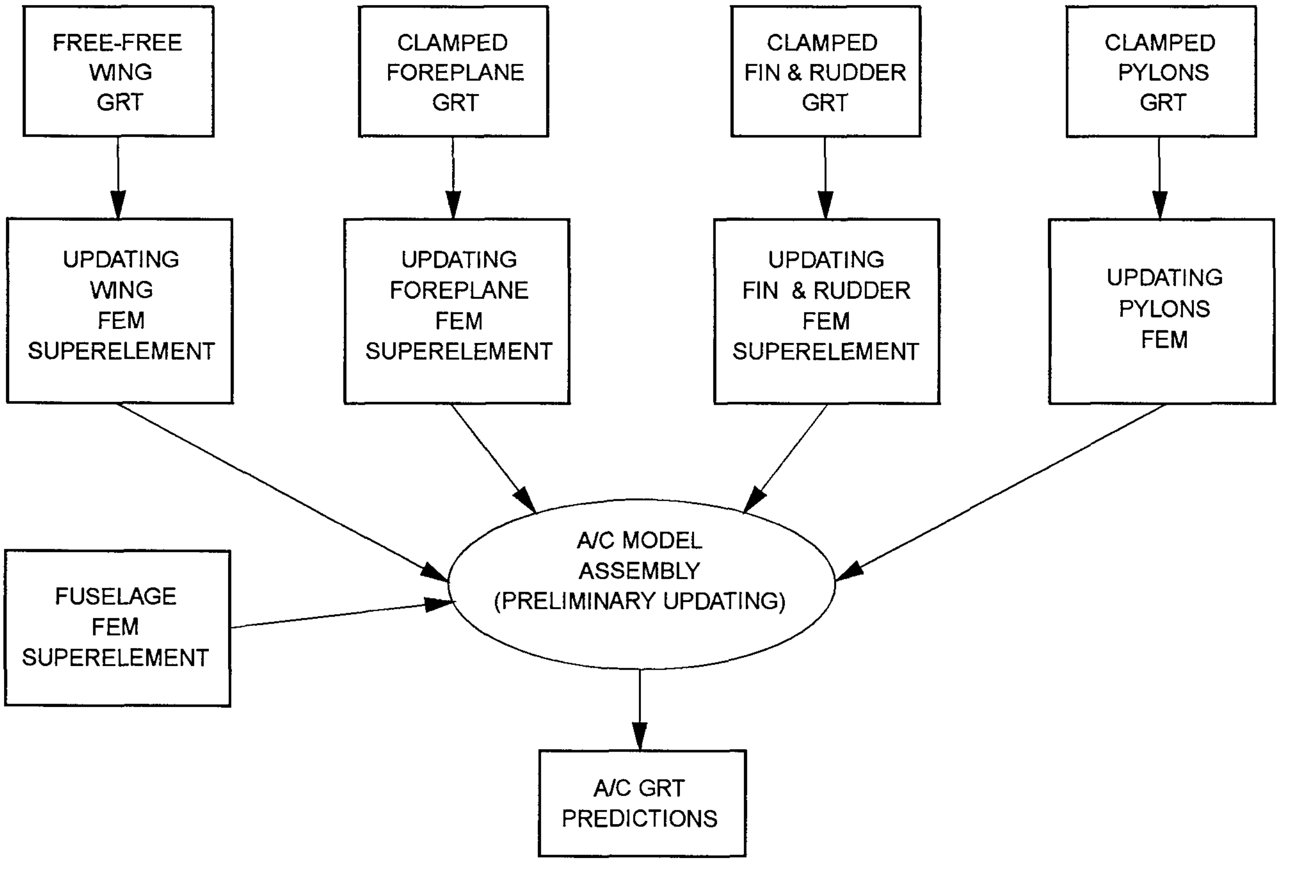

Figure 4: Model Preliminary Update Procedure (Components)

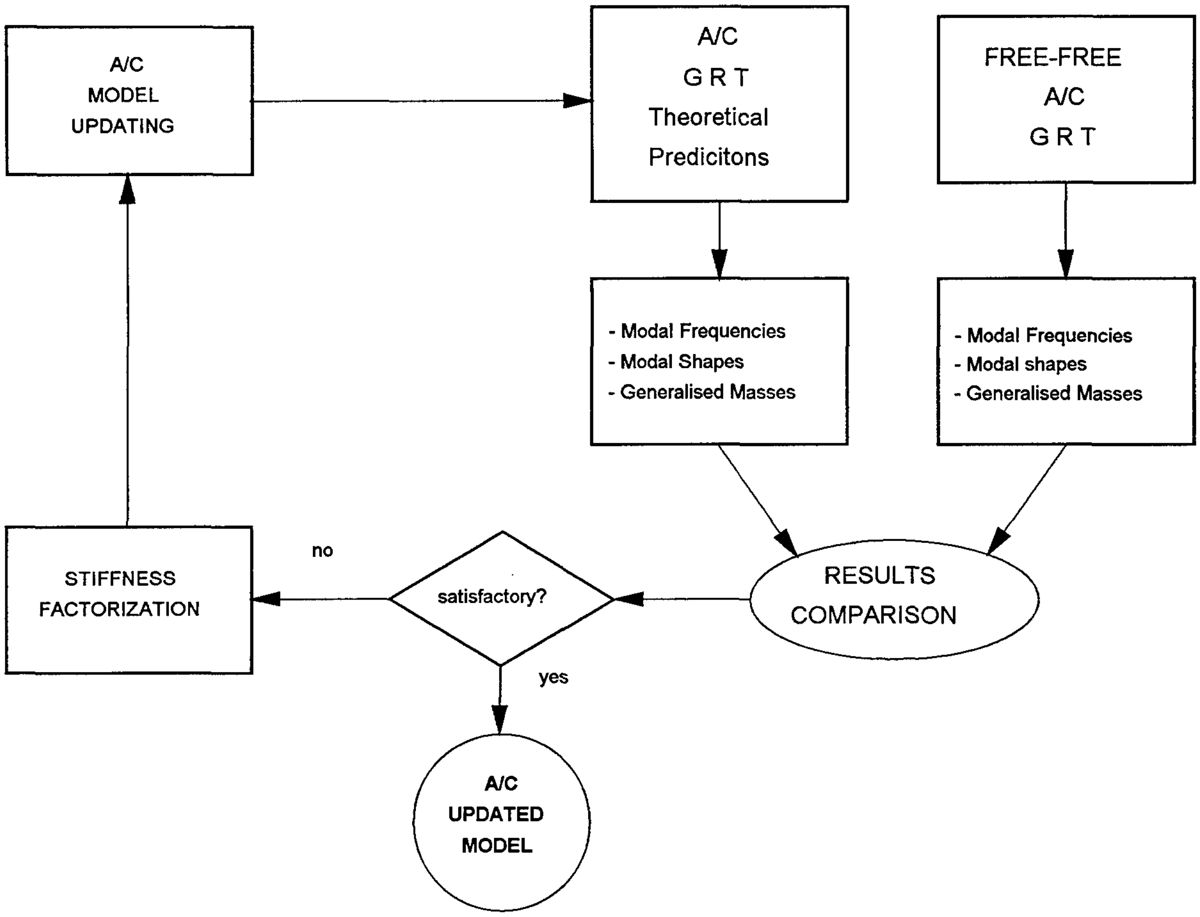

Figure 5: Aircraft Dynamic Model Updating Procedure Based on GRT

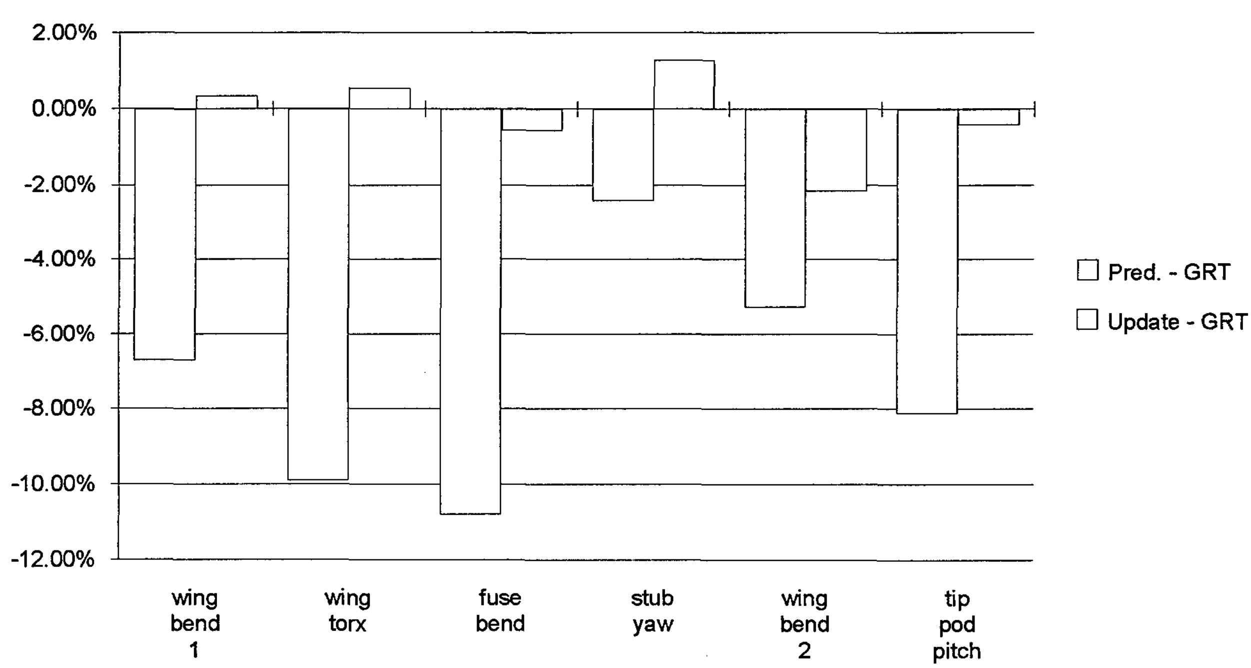

Figure 6: Modal Frequency Percentage Differences

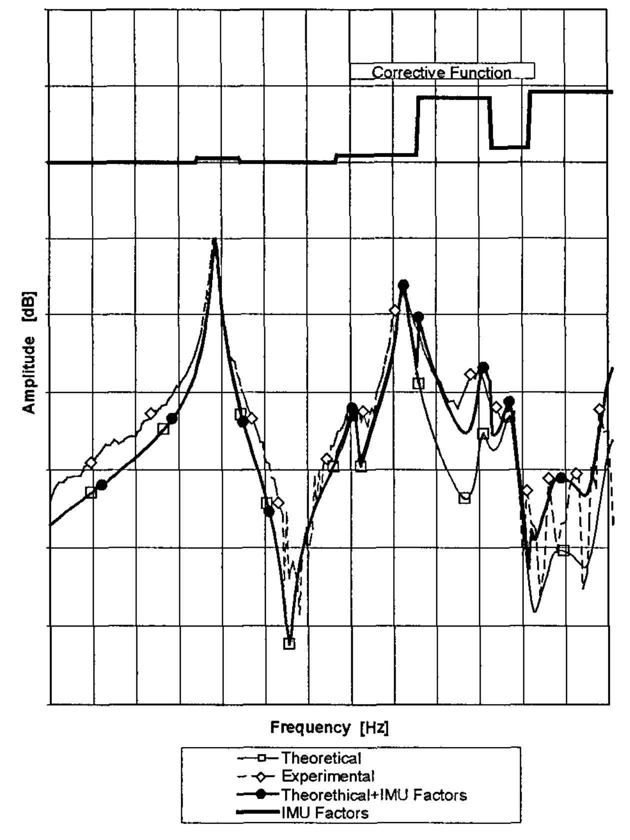

Figure 7:Example of application of a Correction Function

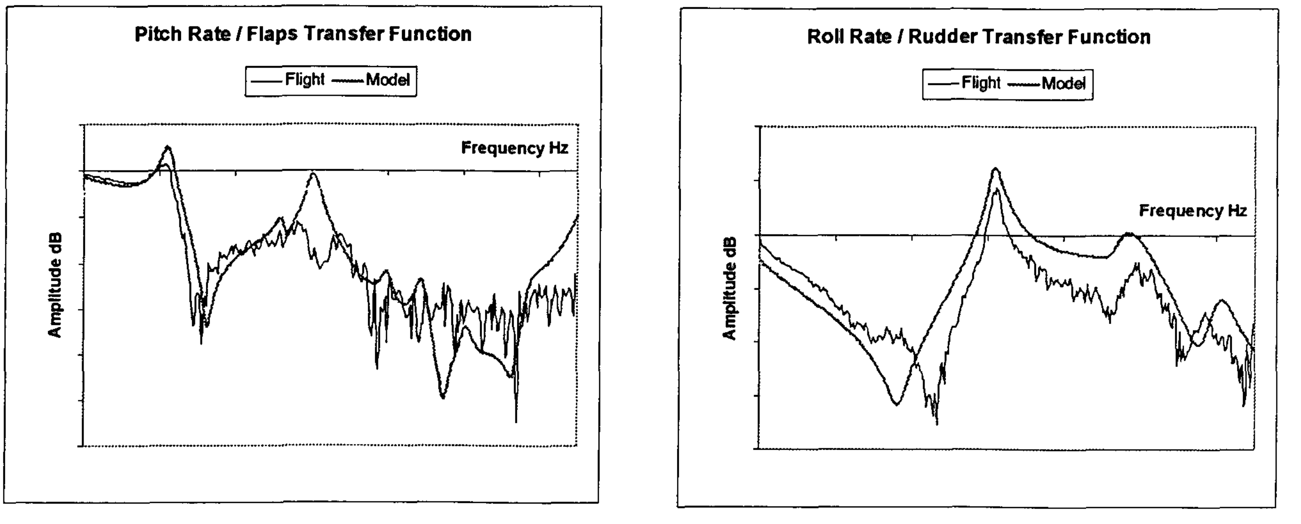

Figure 8: Example of comparison of SCT Flight test data with model predictions